GER-6555

MULTILIN

GE Power Management

Protective Relays

High Voltage Transmission Line Protection with Single Pole Tripping and Reclosing

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INTRODUCTION

In recent years, the increasing construction costs brought on by inflation have imposed economic restrictions on many electric light and power companies, and forced them to intensify their search for reductions in capital investment and operating expenses. Faced with the continuing demand for more and more power in an environmentalist era, many operating companies are seeking, among other things, a means for supplying reliable power with fewer transmission lines and hence reduced capital investment. Since the 1960s, we have seen transmission line voltages climb from 345kV to 500 kV and 765kV, with plans for voltages in the 1100-1500 kV range. Series capacitor compensation has been employed as well as dc transmission to improve capital return, and now attention is moving toward the application of single and/or selective pole tripping on transmission lines with and without series compensation.

SINGLE AND SELECTIVE POLE TRIPPING AND RECLOSING

A relay protection scheme that provides for single pole tripping and reclosing is one that, after it detects a fault and establishes that tripping should take place, will trip only the faulted phase on single-line-to-ground faults and all three phases on all multi-phase faults. In such schemes automatic reclosing is always employed to reclose in the event of a single pole trip and sometimes also for three-phase trips. However, this latter operation is usually optional by selector switch in the field. In general, single pole tripping schemes perform as follows:

1. When a single phase-to-ground fault occurs on an energized transmission line the faulted phase is tripped and automatically reclosed after a suitable dead time. If the fault is cleared everything resets. If the fault is still on the line when the pole is reclosed, all three poles are tripped and no further reclosing takes place.

2. When a multi-phase fault of any kind appears on an energized transmission line all three poles are tripped. At this point, depending on how the scheme is programmed, the breakers could be locked out or, after a suitable dead time, reclosed into the line. In the latter case. if the fault is gone, everything resets. If the fault is still present, all three poles trip and no further reclosing takes place.

3. When energizing a dead line by control switch or supervisory control, if any kind of fault is present on the line, three pole tripping takes place and there is no automatic reclosing.

A protective relaying scheme that employs selective pole tripping would trip only the faulted phase or phases and leave the unfaulted phase or phases in service. Thus, it would trip all three poles for a three phase fault. It would trip the two faulted phases for a double-phase-to-ground fault; it would trip only the faulted phase on a single-phase-to-ground fault; and finally on a phase-to-phase fault it would trip the two faulted phases.

It is interesting to note that there has been some discussion and consideration given to a modified selective pole tripping scheme that would perform as noted above, with the one exception that on phase-to-phase faults only one of the two faulted phases would be tripped to clear the fault. With regard to this latter proposal, the objection has always been raised that such an approach would require one pole of a breaker to interrupt against 1.73 times rated phase-to-neutral voltage. This is outside the normal standard requirements for circuit breakers and could contribute to a significantly higher probability of failure to interrupt.

Because of little or no experience with selective or modified selective pole tripping, there is no data on how it is used. However, it is anticipated that single shot reclosing would be used for all faults with the possible exception of 3-phase faults. In any case, three phase tripping and no reclosing would prevail when closing into a fault.

Also, because of little or no experience with selective pole tripping schemes, before selecting such a scheme, studies should be made to ascertain whether any unusual effects such as resonance or overvoltages could result from having only one pole closed.

POWER TRANSFER VS. SYSTEM IMPEDANCE

Single or selective pole tripping schemes are usually considered for one of the following reasons:

a) To specifically increase the availability of an isolated generating station that is connected to the load center via only one or two three phase transmission lines.

b) To generally increase the reliability of a mesh transmission system on a second or third contingency basis.

The extent to which bath single pole and selective pole tripping can increase the reliability of a transmission system depends on the configuration of the system. The increase in reliability is obtained because tripping of one or two phases does not introduce as much additional impedance into the transmission system as does tripping three phases. Thus, the system tends to be more stable.

If one considers a simplified power system consisting of two sources interconnected by a transmission line, the three phase power transfer across the system is given by the following equation:

$$P = \frac{E_X E_Y}{X} \operatorname{Sin} \delta \qquad (1)$$

where: P = Real power transfer in watts from X to Y.

E_X = The equivalent transmission system line-to-line voltage in volts at the X end of the system

E_Y = The equivalent transmission system line-to-line voltage in volts at the Y end of the system. (Here assumed equal to E_X)

X = The equivalent system reactance in ohms referred to transmission system voltage between the two sources E_X and E_Y

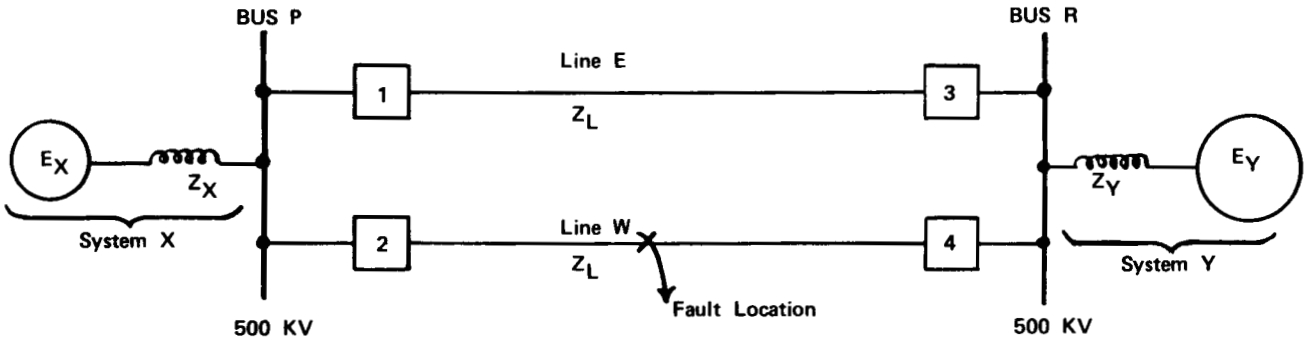
δ = The angle by which the voltage E_X leads E_Y.

If a system is to be reliable it must be relatively stable during abnormal conditions (faults, lines out of service, etc.) as well as during normal conditions. Equation 1 above indicates that the maximum power which can flow across the system is

$$P_{max.} = \frac{E^2}{X} \qquad (2)$$

This, the steady state stability limit, occurs at δ = 90 degrees. The relative stability of a given system similar to that of Figure 1 for different conditions of faults and open phases can be evaluated by means of equation 1 above.

If we assume that the voltages E_X and E_Y are constant voltages behind the transient reactances of the two sources, and X is the sum of the line and machine reactances, then for a given system reactance (X), the angle (δ) between the two voltages is directly related to



Z_{L1} = Positive Sequence Impedance of Lines E & W = 0.6 ohms/mile

Z_{L0} = Zero Sequence Impedance of Lines E & W = 1.50 ohms/mile

Z_{X1} & Z_{X0} = Positive and Zero Sequence Impedance of System X

Z_{Y1} & Z_{Y0} = Positive and Zero Sequence Impedance of System Y

Figure 1

the power flow. For a given power flow, a higher reactance (X), will result in a greater angle δ. The bigger the angle δ the less stable is the system. Thus, for any given required power transfer across the system, the lower the reactance between the points of transfer, the more stable the system. Single and selective pole tripping help to keep this reactance low between the instant when a fault is cleared (by opening less than all three phases) and the instant when the open phases are reclosed.

In order to provide some appreciation for the relative advantages of single and selective pole tripping over three pole tripping, a system consisting of two parallel high voltage transmission lines interconnecting two large systems was constructed in Figure 1 and analyzed in Appendices I, II, and III, and IV.

From Figure 1 it will be noted that the positive sequence impedance of the two lines was assumed as 0.6 ohms per mile which is a normal value for EHV construction. The ratio of zero sequence to positive sequence impedance of the lines was selected as 2.5 which is a rather low value for most EHV circuits. The two equivalent system (X and Y) impedances were assumed to have zero sequence to positive sequence ratios of 1. This is a reasonable assumption since system impedances are comprised of generators and transformers as well as lines. The zero sequence impedance of a unit type generator transformer installation would be in the order of 25 to 30 percent of the positive sequence impedance during transient conditions.

The equivalent power transfer impedances for the system of Figure 1 were evaluated in Appendices I, II, and III for various normal and abnormal system conditions as noted in the second column of Table I. In the calculations it was assumed that all impedances were pure reactance. While this is obviously not the case, the error introduced will not affect the conclusions in any significant way. The third column of Table I indicates the appendix and equation where these impedances were calculated. The calculations were based on each 500 kV line being 100 miles long and the X and Y systems being equivalent to 25 miles and 10 miles of (positive sequence) transmission line impedance respectively. The fault location was assumed to be in the middle of one line.

If in the system of Figure 1 the normal load flow is 1,500 megawatts from system Y to system X

divided over the two lines, then the normal angle across the system for Case 1 in Table I, would be obtained from:

$$P = \frac{E_X E_Y}{X} \text{ Sin } \delta$$

$$1{,}500 \times 10^6 = \frac{(500)^2 \times 10^6}{51} \text{ Sin } \delta$$

$$\text{Sin } \delta = 0.306$$

$$\delta = 17.8 \text{ degrees}$$

For the other conditions of Table I, the angles required to transmit these same 1,500 megawatts under steady state conditions are given in the fourth column of the Table.

It is interesting to note from Table I that the system appears to be quite capable of transmitting the 1500 megawatts continuously for all cases except for the very last where only one single phase was connecting the two systems. The fact that cases 2 and 3 yield exactly the same results is coincidental and results accidentally from the parameters selected for the system. However, it is *generally* the case that the ability of the system to transmit power through a single phase-to-ground fault in the middle of a long line is not vastly different than it is for the condition of having one phase open.

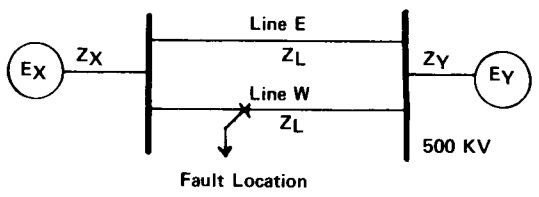
While the above analysis provides a measure of relative stability for the different conditions it does not indicate definitely whether or not any of the fault or open phase conditions would be stable in the transition period (transient stability). Appendix IV utilizes the "equal area" criteria to develop a simple, conservative means for evaluating the transient stability of these cases. No calculations are indicated but it may

TABLE I

EQUIVALENT LOAD TRANSFER IMPEDANCE AS A FUNCTION OF SYSTEM CONDITIONS

Case	Equivalent Load Transfer Impedance Z_{XY}	Calculations Locations	Phase Angle (δ) Between E_X & E_Y Degrees
Case 1 - 2 Lines in Service No Fault	51 ohms	Appendix I - Equation I-4	17.8
Case 2 - 2 Lines in Service ØA to Ground Fault on Line W	60 ohms	Appendix I - Equation I-6	21.1
Case 3 - 2 Lines in Service No Fault - ØA Open on Line W	60 ohms	Appendix II - Equations II-1	21.1
Case 4 - 2 Lines in Service No Fault - ØB & ØC Open on Line W	71 ohms	Appendix II - Equation II-2	25.5
Case 5 - Line W Out of Service No Fault	81 ohms	Appendix III - Equation III-1	29.1
Case 6 - Line W Out of Service ØA to Ground Fault on Line E	107 ohms	Appendix III - Equation III-2	40.0
Case 7 - Line W Out of Service No Fault - ØA Open on Line E	136 ohms	Appendix III - Equation III-3	55.0
Case 8 - Line W Out of Service No Fault - ØB & ØC Open on Line E	333 ohms	Appendix III - Equation III-4	*

* With 333 ohms impedance it is not possible to transmit 1,500 megawatts across the system



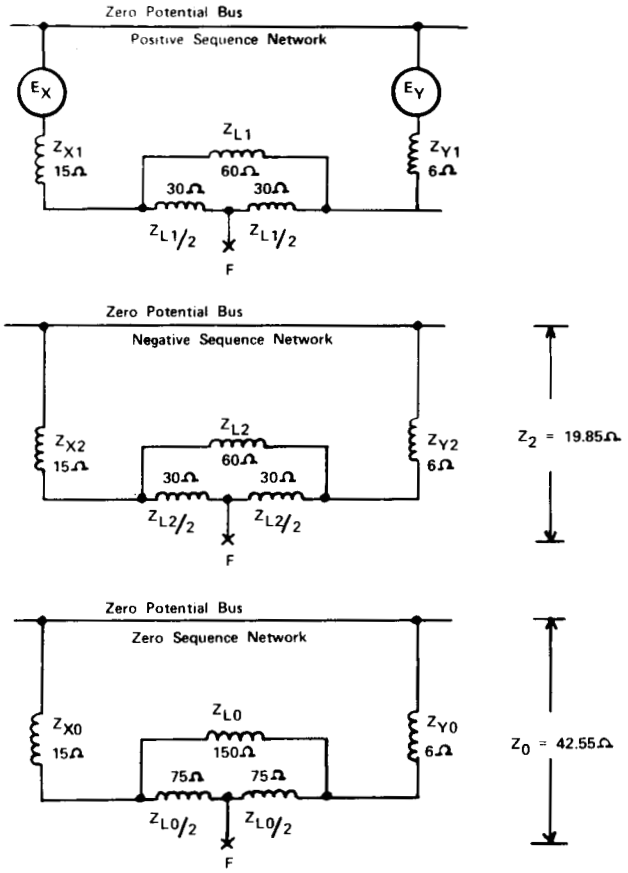


Figure 2

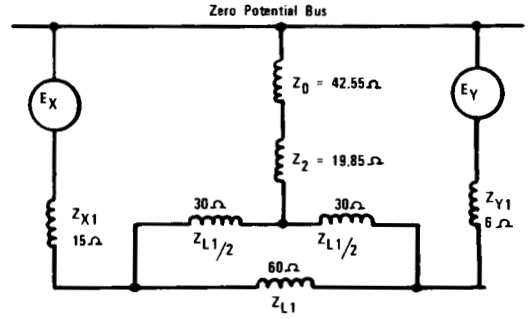


Figure 3

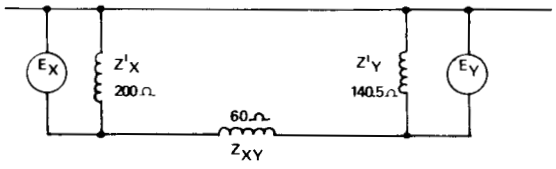


Figure 4

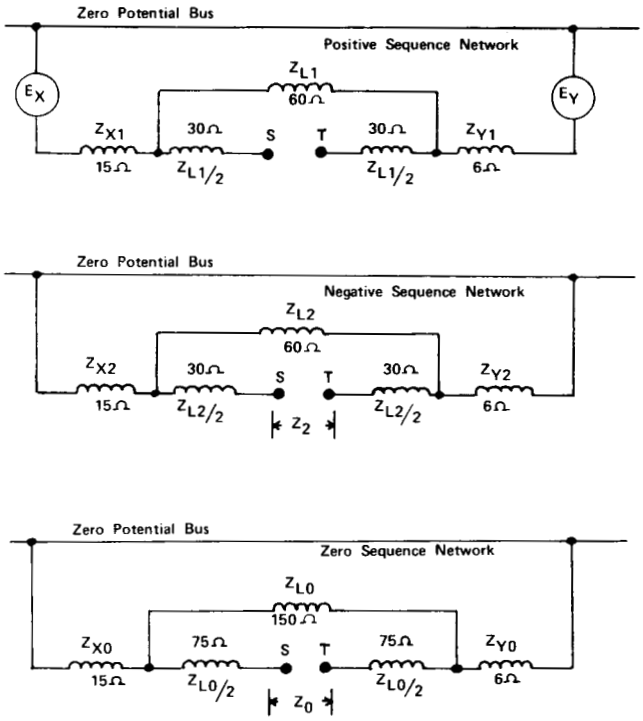


Figure 5

be shown by substituting the values of δ and Z_{XY} in the equations of Appendix IV that all cases are stable except for Case 8 which is a condition that could result when selective pole tripping is employed. Because of the conservative nature of the approach of Appendix IV, Case 8 may in fact be stable but it would require a more comprehensive study to evaluate.

Probably a classical case for the application of single and selective pole tripping is that where an isolated generator or generating station is connected to the system load center over one single transmission line. A reasonable example of such an application would be a 1,000 MW unit type generator connected through 100 miles of 500kV transmission line to a system with an equivalent impedance equal to about 10 miles of 500kV line. The characteristics of the line are assumed to be the 0.6 and 1.5 ohms per mile for the positive and zero sequence reactances respectively. The generator positive sequence transient reactance was assumed as 28 percent

and the negative sequence reactance as 20 percent. The unit transformer was assumed to have a positive and zero sequence reactance of 10 percent with all impedances on a 1,000 MVA base.

TABLE II

Case	Power Transfer Impedance Ohms	Power Angle Across System Degrees
No Fault All Phases Closed	161	40.2
Ø to Ground Faults	272	*
No Fault One Phase Open	240	74.2
No Fault Two Phases Open	483	*

* Cannot transmit 1,000 megawatts across the system with these impedances

Table II gives the results of steady state calculations similar to those used to establish the values in Table I. In this case the single phase-to-ground fault was assumed to be at the generator end of the line which is the worst case for this system. From Table II it will be noted that the system could not transmit the 1,000 megawatts continuously during a phase-to-ground fault or for the case with two phases open. While it can transmit this power with only one phase open, a transient analysis based on Appendix IV indicates a marginal situation. However, because of the conservative nature of these calculations, it is anticipated that this system could survive a single phase-to-ground fault that is cleared in several cycles by opening only the faulted phase. On the other hand it is questionable whether it could withstand a double-phase-to-ground fault and the switching of two phases.

It is interesting to note that, had the ratio of zero sequence to positive sequence line impedance been assumed equal to three, (a more normal ratio than 2.5 at EHV), the results would have indicated single line to ground faults to result in somewhat lower power transfer impedance, while open conductors would have produced higher values for otherwise similar conditions.

The two simple studies discussed above, in addition to other complete studies made over the years, lead to the following general conclusions regarding *transmission line* faults:

a) The ability to transfer power during a fault decreases as the fault moves closer to a source or receiving terminal.

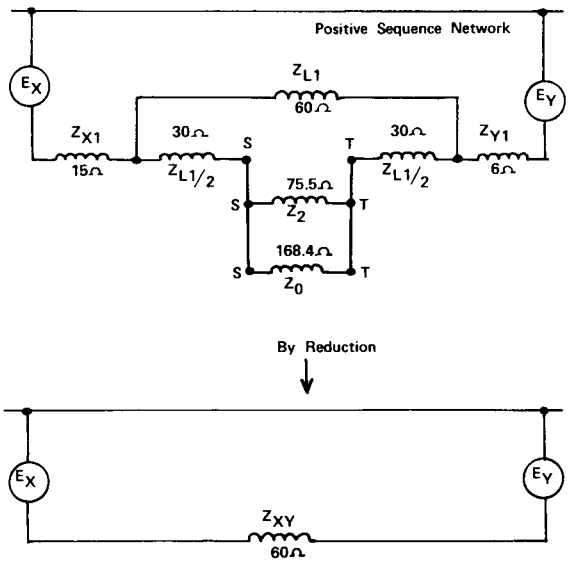


Figure 6

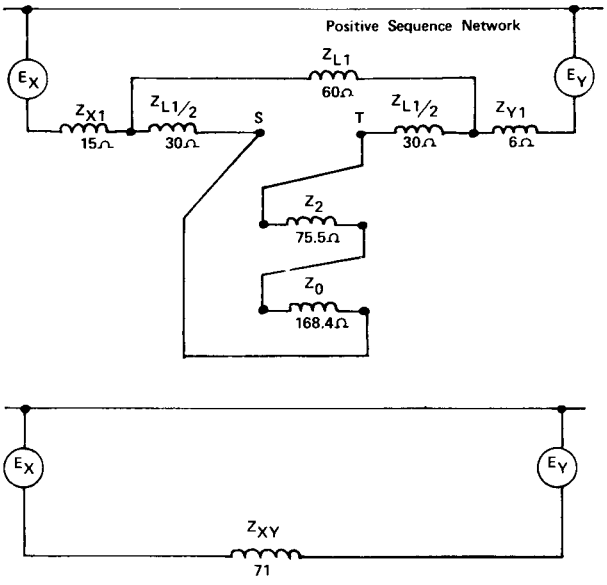


Figure 7

b) The ability to transfer power during a fault decreases as the severity of the fault increases from single-phase-to-ground, to phase-to-phase, to double-phase-to-ground, to three-phase.

c) The ability to transmit power over a transmission line decreases as more phases are open.

d) The ability to transfer power increases for any fault or open phase(s) as the number of tie lines increases.

e) While not apparent from the Tables, it can be shown that for series compensated lines, the ability to transfer power with two poles open becomes much more difficult relative to the case with one pole open than it is for ordinary lines. This is the case because for this condition the negative and zero sequence networks are connected in series (see Appendix II and Figure 7) and because series capacitor compensation is much more effective in the negative sequence network than it is in the zero sequence network.

In the total consideration of the type of scheme to select, the following points should be evaluated against the cost and complexities of the different schemes:

1) Single pole and selective pole tripping schemes offer the greatest gain to system stability when only one tie line exists. Where only two tie lines exist it is reasonable to assume that one could be out of service when a fault occurs on the second line. Thus, some sort of single or selective pole tripping scheme could provide benefits comparable to those where only one line exists. However, as the number of ties increase beyond two, the statistical advantages of single and selective pole tripping fall off rapidly.

2) Single-phase-to-ground faults are very much more prevalent than phase-to-phase and double-phase-to-ground faults.

3) Operation of a single tie with only one phase closed (as would be the case with selective pole tripping during the dead time before reclosing and after tripping two poles for a double line to ground fault) results in a rather unstable system. This, in practice, may not be any better than with all three poles being tripped, so that selective pole tripping may offer no advantage over single pole tripping.

4) A modified selective pole tripping scheme that initiates tripping of only one phase for a phase-to-phase fault may overstress the circuit breaker.

5) Because the ability of the system to transmit power is very nearly the same for one phase open as it is for a single-phase-to-ground fault, and because the system must be able to ride through reclosing dead time with at least one pole open, extra high speed clearing of single-phase-to-ground faults does not appear to be a requirement for stability in those applications where single pole tripping is of value.

INTEGRATED VS. SEPARATED SCHEMES

Single pole tripping schemes can be constructed in many different ways utilizing different types of devices. However, the basic approaches may be divided into two categories, "Integrated Schemes" and "Separated Schemes".

It is obvious that any single pole (or selective pole) tripping scheme must make two basic determinations:

(a) Whether or not the fault is in the trip zone

(b) Which phase or phases are faulted.

In the case of (b) above, a single pole tripping scheme needs to determine whether it is a multi-phase fault or a single phase fault and in the event of a single-phase-to-ground fault it must establish which phase is faulted. On the other hand, a selective pole tripping scheme must establish which phase or phases are faulted for all types of faults.

An Integrated Single Pole (or Selective Pole) Tripping Scheme utilizes the same measuring functions to perform both (a) and (b) above while a Separated Scheme would use one set of functions to establish (a) and a separate set to determine (b).

If one opts for an integrated scheme, then the selection of the measuring units is restricted to those that can determine which phase or phases are faulted, as well as whether the fault is internal or external. For example, an integrated scheme could not satisfactorily employ zero sequence directional overcurrent relays for ground fault protection because in themselves these ground relays could not determine which of the three phases were faulted. A better selection would be three single phase directional ground distance relays.

If a selective pole rather than a single pole tripping scheme, is under consideration and if it is to be an integrated scheme, then the phase fault relays cannot consist of only one polyphase device for all three pairs of phases, because this type of device cannot by itself ascertain which pair of phases is faulted. A more suitable approach would be to use three single phase units having directional ohm characteristics. A rather direct approach to an integrated scheme is to use separate phase comparison schemes for each individual phase. Such an approach, termed segregated phase comparison, could be used for selective as well as single pole tripping.

While other examples could be cited, those already mentioned make it clear that with regard to single or selective pole tripping, there is an interdependence between the nature of the scheme and the type of measuring functions required.

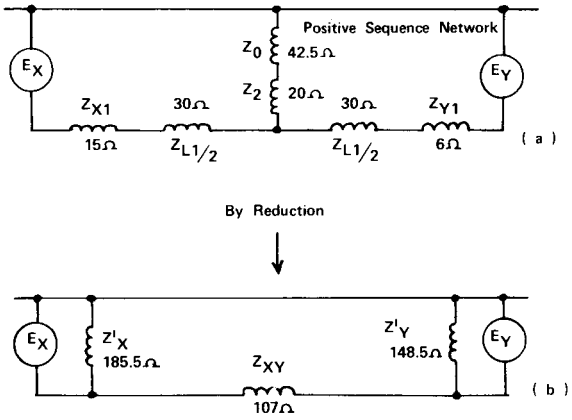


Figure 8

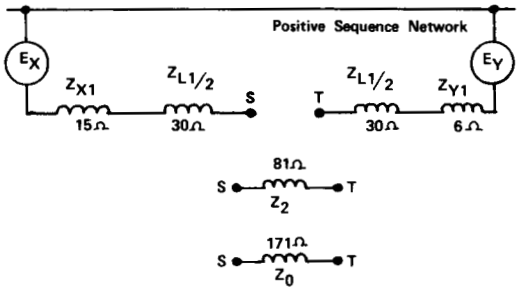


Figure 9

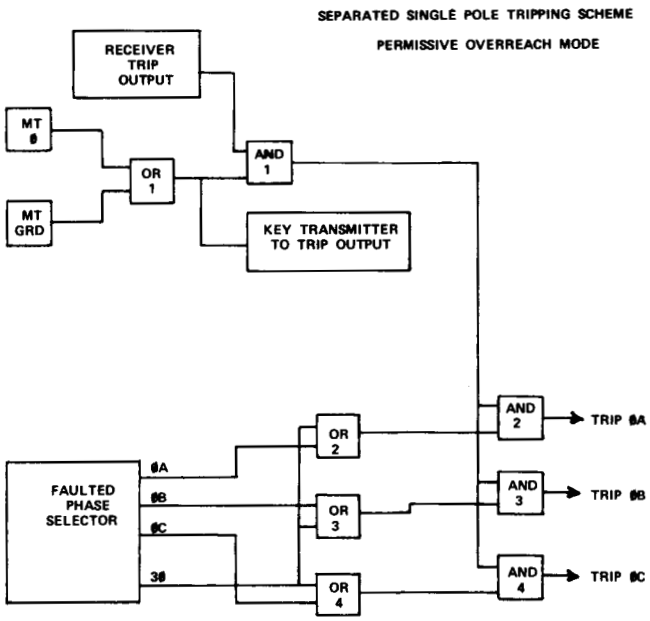


Figure 10

SEPARATED SCHEMES

Separated schemes will employ separate devices called Phase Selectors in addition to the regular complement of protection. For example, if it is desired to utilize a directional comparison blocking scheme to protect a line that will employ single pole tripping, then the standard complement of relays for a directional comparison blocking scheme would be used in addition to the separate phase selectors. The directional comparison scheme would determine whether or not to trip while the phase selectors would route the trip signal to the proper pole or poles. If, on the other hand, it was a phase comparison scheme that was desired, the same phase selector devices could be employed with standard phase comparison scheme. In any case, however, three electrically separate pairs of trip outputs are required to facilitate independent pole tripping of two circuit breakers.

Figure 10 illustrates a separated single pole tripping scheme that is operating in a permissive overreaching transferred tripping mode. The measuring functions (MT/Ø) and MT/GRD) are symbolic of any suitable set of standard directional phase and ground (distance) relays. The determination of whether the fault is internal or external is made in the upper part of this figure in the traditional manner. The phase (MT/Ø) and ground (MT/GRD) functions are set so that they can see any fault on the protected lines operates to key the local transmitter to its TRIP frequency via OR1. The receipt of an output TRIP signal from the local receiver concurrent with the output from OR1 produces an output from AND1. An output from AND1 indicates an internal fault.

Concurrently, the Faulted Phase Selector function must determine which phase or phases are faulted and produce the associated outputs. The logic in the phase selector would be such that for any fault other than a single-phase-to-ground fault it would produce a three-phase output. For a single-phase-to-ground fault it would produce an output associated with the faulted phase. Thus, for a single-phase-to-ground fault only one of OR2, OR3, or OR4 would produce an output to its respective AND. The second output to these AND's would come from AND1 indicating an internal fault. The output from one of these AND's would then trip the proper single phase. For any multiphase fault, the three-phase output from the phase selector would energize all three OR's and hence AND2, AND3, and AND4, to trip all three poles.

It should be recognized that the phase selector in the single pole tripping scheme described above needs only to distinguish between multi-phase faults and single-phase-to-ground faults, and in the latter case to ascertain which phase is faulted. In the case of selective pole schemes the phase selector in addition would be required to determine the exact type of multi-phase fault. Such an additional requirement could increase the complexity of this device by a substantial factor without providing any significant additional system integrity in many, if not all, cases.

The separated approach to single or selective pole tripping permits a great deal of flexibility in the selection of a protective scheme and the type of measuring functions that could be used. This makes it easier to provide primary and back-up protection that operate in different modes and use different measuring functions. The basic disadvantage of a separated scheme is that it requires some additional measuring functions to perform the phase selection.

INTEGRATED SCHEMES

As opposed to separated schemes, integrated schemes use the same measuring functions to determine which phase or phases to trip as are

used to establish whether the fault is internal or external to the zone of protection. A simplified functional representation of such a scheme operating in a permissive overreaching transferred tripping mode is illustrated in Figure 11.

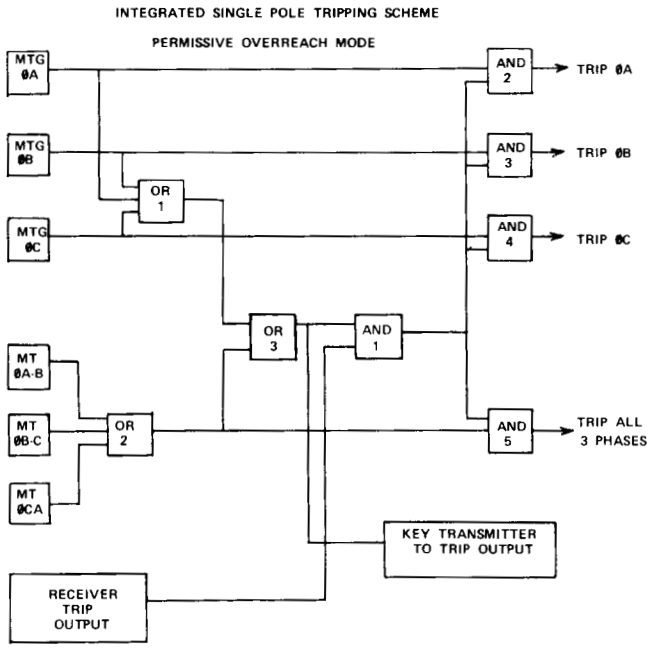


Figure 11

This diagram indicates three individual single-phase directional ground distance relays (MTG) and three directional phase distance relays (MT). If this arrangement is to perform properly then it is necessary that the MTG ground measuring functions be selective among themselves so that for any single phase-to-ground fault only the faulted phase unit operates. For any multi-phase fault one or more of the phase MT units must operate. These same MT and MTG functions also determine, in conjunction with the channel, whether the fault is internal or external.

The operation of the scheme is such that when a fault in the trip direction occurs, one of the MT or MTG units operates to produce an output from OR1 or OR2 which in turn results in an output from OR3. This output from OR3 keys the local transmitter to the TRIP frequency, and it also provides one of the inputs to AND1. If the fault is internal, the remote end of the line will be sending a TRIP frequency signal which will produce a TRIP output from the local receiver. This TRIP output provides the second input to AND1 which then produces an output to indicate a desire to trip. This desire to trip signal is fed to ANDs 2 through 5 and depending on which measuring unit or units detected the fault either one pole or all three poles would be tripped.

If a selective tripping scheme is desired it would be necessary to separate the MT phase tripping functions so that only the pairs of phases that are faulted are actually tripped.

Another integrated single pole tripping scheme if functionally illustrated in Figure 12. This scheme operates in a phase comparison mode, utilizing three segregated phase comparison functions, one per phase. Each phase has its own fault detector (FD) and squaring amplifier (SQ. AMP.) as well as its own transmitter and receiver. The scheme utilizes standard phase comparison techniques except for the fact that each of the three phase comparisons is made on the basis of single phase currents.

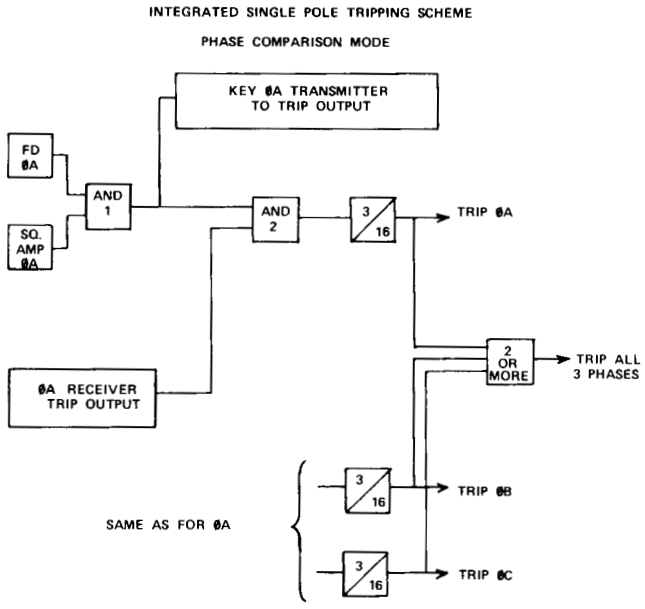


Figure 12

Referring to Figure 12, when a fault involving phase A occurs the associated fault detector (FD) picks up as does the squaring amplifier (SQ. AMP.). This results in AND1 producing half cycle outputs which are in phase with the positive half cycles of the phase A current. This produces half cycle keying of the transmitter to the TRIP frequency and simultaneous half cycle inputs to AND2. If the fault is internal to the protected zone, the local receiver will be producing TRIP outputs during the same half cycles as a result of the remote transmitter being keyed by its associated FD and SQ. AMP. functions. The output from the local receiver supplies the second input AND2. If these two inputs to AND2 are coincident for three milliseconds or more it indicates that the phase A currents *entering both* ends of the line are less than about 120 degrees out of phase and the fault must be internal. This produces a trip output to Phase A.

If the fault were to involve more than one phase, then more than one phase comparison would take place simultaneously. If the fault were internal, trip outputs would be channeled to all three phases via the 2-OR-MORE logic. Two or more inputs to this logic produce an output that trips all three poles.

In this case, if selective pole tripping is desired, the 2-OR-MORE logic would be eliminated.

While both Figures 11 and 12 represent integrated schemes there are two very apparent differences:

1) The scheme of Figure 11 involves only one channel while that of Figure 12 requires three.

2) The scheme of Figure 11 is capable of providing three-pole second zone back-up protection for remote bus faults by the addition of a timer after OR3. The scheme of Figure 12 cannot provide this back-up protection because phase comparison is a true differential type of scheme.

HYBRID SCHEMES

If in the equipment indicated as "Faulted Phase Selector" in the separated scheme of Figure 10 there are some functions required that are similar to those used in the fault detecting equipment, a hybrid scheme can be used. As the term implies, a hybrid scheme is one that has some device or devices dedicated to phase selection, other devices dedicated to fault detection and still other devices that are common to both functions. This kind of arrangement would in general be more economical than a separated scheme. However, it would generally restrict the type of measuring functions used.

OTHER CONSIDERATIONS

The above discussion of the different schemes, along with Figures 10 through 12, are very general in nature and cover only the broadest concepts. There are a number of significant details that can affect the suitability of any given scheme for any given application. Some of these are enumerated and discussed below.

Line Side vs. Bus Side Potentials

Because single and selective pole tripping schemes must perform properly and detect faults that occur or evolve during the time that one or more poles are open, the location of the potential supply to the relays can be important. If one phase of a transmission line is open at both ends while the other two phases are energized the "dead" phase voltage does not go to zero. The voltage on this open and unfaulted phase will have some magnitude and angle that depends on:

a) Whether or not the line is transposed, and if it is not transposed, which phase is open.

b) Whether or not shunt reactors are employed, and if they are, the amount of compensation they afford and the configuration of the reactors.

c) Load flow in the two intact phases.

When the potential transducers are located on the bus side of the circuit breaker, the three phase voltages tend to stay relatively well balanced when one, or even two phases, are open.

While the phase comparison scheme illustrated in Figure 12 is unaffected by these conditions because no potential supply is required, all schemes using relays that require potential must be designed to mitigate the effects of any possible misoperation during the time that one or more poles are open. This requirement tends to make distance relaying schemes utilizing line side potentials somewhat more complex than those that employ bus side potentials.

Tripping vs. Blocking Schemes

In traditional blocking type schemes no blocking signal is sent in the quiescent state. On the other hand, in permissive tripping and unblocking schemes, the blocking signal is normally sent in the quiescent state. In these latter types of schemes it is usually necessary to provide some means for tripping a circuit breaker when picking up a dead line that is faulted. Traditionally in three pole schemes this is accomplished by means of circuit breaker auxiliary switches or sensitive current detectors that key the transmitters to the unblock or trip frequency when the associated circuit breaker is open. Another approach would be to utilize a "Line Pick-up Scheme" that permits tripping on the operation of a fault detector alone, when a circuit breaker is closed or reclosed to pick up a dead line.

In general this same situation exists when single pole and selective pole schemes are used in unblocking or permissive modes. However, when only one single channel is used, as in the schemes of Figures 10 and 11, more detailed consideration must be given to this aspect of the design, because opening any one pole would key the transmitter while the other two poles are closed and carrying load. This could result in a false trip in the unlikely event that a nearby external fault were to occur during the time one pole were open unless provisions are included to mitigate this situation. In general this is not a consideration in the segregated phase comparison scheme of Figure 12 because it utilizes one communication channel per phase. It is also not a consideration in blocking schemes because no blocking signal is sent in the quiescent state.

Evolving Faults

An evolving fault is one that starts as a single-phase-to-ground fault and then involves additional phases during the time that the initial fault is being cleared or during the dead time of the original faulted phase.

Single pole and selective pole schemes should provide some means for detecting and clearing evolving faults. The method for accomplishing this will depend on a number of different factors. If the scheme employed is the segregated phase comparison scheme of Figure 12, the ability to detect evolving faults tends to come naturally, because each phase is protected on an individual basis. On the other hand, in schemes that utilize relays that require potential supplies, it is necessary, in the design of the logic, to consider the types of measuring functions employed, and whether or not line side potential sources are used in order to insure the desired performance.

Line Construction-Fault Resistance

In general, if ground distance relays are to be used in a protective scheme it is important to recognize that they do have some limitation with regards to high fault resistances. Such relays tend to have difficulties with single-phase-to-ground faults initiated by trees or brush fires. However, because most single or selective pole tripping schemes are used on long or medium length lines this problem is somewhat mitigated by the large reach settings required to protect them. Where such conditions can exist, or where the line construction is such that no shield wires exist and high tower footing resistance to ground is prevalent, careful consideration must be given before ground distance relays are applied. High ground fault resistance, in combination with heavy load transfer, can make it difficult for the segregated phase comparison scheme of Figure 12 to detect single-phase-to-ground faults.

Open Pole Operation

When one or two poles of a transmission line are open, an asymmetrical condition exists on the system that results in negative and zero sequence current flow throughout the system which in turn produce negative and zero sequence voltages throughout the system. Negative and zero sequence directional relays located at the terminals of a transmission line that is operating with one or two open phases will receive voltages and currents that indicate to the relays at both terminals the impression that an internal fault exists. If sufficient magnitude of current is flowing, such devices could produce continuous trip outputs during the time that one or more poles are open. To similar relays located at both ends of a parallel line, the condition resembles an external fault. Other similar relays located elsewhere on the system may see the condition as either an internal or an external fault.

In any case, schemes that employ zero or negative sequence relays must be designed with these points in mind because the continuous output of a tripping relay can continue to activate the circuit breaker back up protection during the time that one or two poles are open, and could also result in a re-trip when the open pole(s) is reclosed.

Circuit Breaker Failure Back-up Protection

In single pole and selective pole tripping schemes, it is necessary to consider factors regarding circuit breaker failure back-up protection that are somewhat different from those involved in three pole tripping schemes.

If a circuit breaker pole fails to interrupt when attempting a single pole operation, it is necessary to trip all three poles of the failed breaker plus all the back-up circuit breakers. In this regard the operation is no different than any three pole scheme. However, if a circuit breaker effects a successful single pole trip, during the dead time of the faulted phase, the two good phases are still carrying current. Thus, single and selective pole tripping schemes must utilize segregated pole current detectors that must, in the logic of the overall scheme, be associated individually with the devices that determine which phase is faulted. With such an arrangement the scheme will not operate incorrectly as a result of current continuing to flow in the healthy phases of a line during the time that one pole is open.

The approach to the scheme of current breaker failure back-up protection must be coordinated with the basic line protection scheme selected.

Sensitivity

In general, the sensitivity of the protection scheme to all kinds of faults will depend on the type of measuring functions used. For example,

zero or negative sequence relays can be more sensitive to very high resistance ground faults than ground distance relays or segregated phase comparison relays. However, if negative or zero sequence relays are used, some other device will have to establish which phase is faulted. The ability of distance relays to accommodate high resistance faults will increase with reach settings as will their overall sensitivities. On the other hand, segregated phase comparison schemes, because the fault detectors may have to be set above full load current in order to prevent continuous phase comparison, tend to become less sensitive on long, heavily loaded lines.

It is also interesting to note that blocking schemes can trip sequentially on weak infeed from one terminal while unblocking and permissive tripping schemes, unless modified, require both ends to see the fault before either end can trip.

Security

In any protection scheme there is always a compromise between security and dependability. While both these measures of performance are affected by such factors as operating errors, faulty channels and coupling equipment, improper applications, incorrect CT and PT connections as well as basic relay performance, it is safe to say that false trips tend to be considerably more prevalent than do failures to trip.

The use of two separate sets of protection (primary and back-up) tends to reduce overall security and increase overall dependability. Thus, it is important to use a scheme (or schemes) that is inherently most secure. As a general rule secure schemes will be those with:

a) simple application rules

b) simple installation and test requirements

c) a minimum of protection equipment

d) a minimum of channel equipment.

There is probably no one scheme that is universally applicable and capable of providing 100 percent performance. When selecting a single pole or selective pole tripping scheme, consideration should be given to the selection of a relatively simple scheme that may initiate an occasional three pole trip for single-phase-to-ground faults, as against, a relatively complex scheme that *theoretically* will never trip more than the faulted phase(s).

Relay Transient Behavior

While the degree may vary, all measuring functions have a transient response to faults that is different from their steady state response. High speed relays operate during the time that the power system is in a transient state. Thus, the important characteristics of any protection scheme are those that relate to the transient conditions on the power system immediately after a fault occurs, during the presence of the fault, and immediately after the fault is cleared. These characteristics can only be completely evaluated by extensive testing on an analog model of the power system. Only in this way is it practical to apply thousands of faults of different initiation angles and locations for different system conditions and observe the actual relay performance.

Series Compensated Lines

In general, the considerations governing the protection of series compensated lines tend to be more complex than those for ordinary uncompensated circuits. The addition of single or selective pole tripping to this protection can further complicate the situation.

On the surface it appears that segregated phase comparison schemes are naturally suited for such applications. However, schemes using distance and directional fault detectors with additional phase selectors may prove to be superior in performance while still maintaining a high level of security as a result of using only one channel.

CONCLUSIONS

Single and selective pole tripping schemes may be used to maintain a desired level of system integrity while minimizing transmission line expenditures. In general, these schemes will be most effective on those portions of the system where relatively few interconnections exist. While selective pole tripping may superficially appear to provide more margin than single pole schemes in the preservation of system stability, it seems unlikely that in those actual applications where single pole tripping is warranted that selective pole tripping will provide any significant advantages.

APPENDIX I

This appendix evaluates the equivalent impedance between the two system (X & Y) sources of Figure 1 for the conditions of bath lines in service and normal, and for the same conditions except a phase-to-ground fault in the middle of Line W.

Assume a 500kV system as in Figure 1 with Lines E and W each 100 miles in length. Assume that the equivalent impedance of System X is equal to that of 25 miles of 500kV line and that of System Y is equal to 10 miles of line. In addition let the zero sequence and positive sequence system impedances be equal.

Thus:

Z_{L1} = 100 x 0.6 = 60 ohms
Z_{L0} = 100 x 1.5 = 150 ohms
Z_{X1} = 25 x 0.6 = 15 ohms
Z_{X0} = 25 x 0.6 = 15 ohms
Z_{Y1} = 10 x 0.6 = 6 ohms
Z_{Y0} = 10 x 0.6 = 6 ohms

With the system intact the effective impedance between busses P&R is:

$$\frac{Z_{L1}}{2} = 30 \text{ ohms} \qquad \text{I-1}$$

The effective impedance between the source in System X and the source in System Y is:

$$Z_{X1} + \frac{Z_{L1}}{2} + Z_{Y1} = 15 + 30 + 6 = 51 \text{ ohms} \qquad \text{I-2}$$

Consider now a single phase-to-ground fault in the middle of line W. During the time that the fault is on this line the system sequence impedances are as indicated in Figure 2 assuming that the negative sequence impedance is equal to the positive sequence impedance.

The equivalent impedance between point F and the zero potential bus in the negative sequence network can be shown to be:

$$Z_2 = 19.85 \text{ ohms} \qquad \text{I-3}$$

The equivalent impedance between point F and the zero potential bus in the zero sequence network can be shown to be:

$$Z_0 = 42.55 \text{ ohms} \qquad \text{I-4}$$

The equivalent circuit that determines the stability of the system is the combination of the three networks of Figure 2 as illustrated in Figure 3. Figure 4 illustrates the reduction (by successive wye-delta and delta-wye transformations) of Figure 3 to yield the impedance Z_{XY} which determines the load transfer capability of the system as indicated by the following equation:

$$P = \frac{E_X E_Y}{X_{XY}} \sin \delta \qquad \text{I-5}$$

where:

P is the real power transfer across the system from X to Y.

δ is the angle by which E_X leads E_Y. X_{XY} is the reactive component of Z_{XY} and is essentially equal in magnitude to Z_{XY}.

It will be noted from Figure 4 that with the single phase-to-ground fault in Line B the equivalent impedance across the entire system is:

$$Z_{XY} = 60 \text{ ohms} \qquad \text{I-6}$$

This is only about 20 percent higher than under normal conditions as can be noted from equation I-2 above.

APPENDIX II

This appendix evaluates the equivalent impedance between the two system (X and Y) sources of Figure 1 for the conditions of one and two phases open on Line W with Line E in service.

Assume the same 500kV system as in Figure 1 and as considered in Appendix I except now assume that instead of being faulted, both lines E and W are in service except that one or two phases of Line W are open. The individual sequence networks for these conditions are illustrated in Figure 5.

For the case of only one conductor open the networks are interconnected by connecting points S in all three networks together and connecting points T in all three networks together. This results in the arrangement illustrated in Figure 6. For this condition the equivalent impedance that controls the power transfer is:

$$Z_{XY} = 60 \text{ ohms} \qquad \text{II-1}$$

Figure 7 depicts the case for two conductors open on Line W. For this case the zero sequence and negative sequence networks are in series with each other and inserted between points S and T in the positive sequence network. This results in an impedance:

$$Z_{XY} = 71 \text{ ohms} \qquad \text{II-2}$$

APPENDIX III

This appendix evaluates the equivalent impedance between the two system (X and Y) sources of Figure 1 with Line W out of service and everything else normal, with Line W out of service but a single phase-to ground fault in the middle of Line E, with Line W out of service and one phase open on Line E, and with Line W out of service and two phases open on Line E.

Using the values of impedance from Appendix I, the equivalent impedance for the normal condition with Line W out of service is:

$$Z_{XY} = 15 + 60 + 6 = 81 \text{ ohms} \qquad \text{III-1}$$

If a single phase-to-ground fault is now applied in the center of Line E, the equivalent circuit is illustrated in Figure 8a. Figure 8b gives:

$$Z_{XY} = 107 \text{ ohms} \qquad \text{III-2}$$

for the case of a single phase-to-ground fault.

For the condition of one phase open, refer to Figure 9. By connecting all the S points together and all the T points together the equivalent impedance may be evaluated to be:

$$Z_{XY} = 45 + \frac{81 \times 171}{252} + 36$$

$$Z_{XY} = 81 + 55 = 136 \text{ ohms} \qquad \text{III-3}$$

For the condition of two phases open the negative and zero sequence impedances are connected in series and in turn connected in series between points S and T in the positive sequence networks. For this case the value obtained for the impedance is:

$$Z_{XY} = 45 + 252 + 36 = 333 \text{ ohms} \qquad \text{III-4}$$

APPENDIX IV

This appendix illustrates a simple approximate approach that may be used to evaluate the ability of a system to withstand a sudden change in impedance without losing stability.

Consider a system similar to that of Figure 1 and assume that under normal conditions it is operating with a power flow of P_T across the system. Let the power transfer impedance for this condition be represented by X_a and assume that the voltages $E_X = E_Y = E$. The angle across the system (δ) would then be equal to δ_1 in Figure IV-A. Note that Figure IV-A is just a plot of equation 1 for two different values of X, namely X_a and X_b.

Consider now that a disturbance occurs which causes the system initial power transfer impedance X_a to change to a somewhat larger value equal to X_b. At the instant this occurs, the power flow across the lines goes down as indicated by equation 1. Assuming that the governors on all the prime movers on the systems are not fast enough to respond, the generators will continue to receive the same input powers. With the load on the system remaining unchanged and the power flow across the lines diminished, the machines at the receiving end of the system will slow down, while those at the sending end will accelerate. The angle δ_1 will increase toward δ_2 but will overshoot somewhat. The equal area criteria of stability states that the transient overshoot will not result in a condition of instability if the area A_1 is smaller than the area A_2.

The area A_1 given by the following equation

$$A_1 = \int_{\delta_1}^{\delta_2} \left(P_T - \frac{E^2}{X_b} \text{ Sin } \delta\right) d\delta \qquad \text{IV-1}$$

The area of A_2 is given by

$$A_2 = \int_{\delta_2}^{(\pi - \delta_2)} \left(\frac{E^2}{X_b} \text{ Sin } \delta - P_T\right) d\delta \qquad \text{IV-2}$$

If the integration is performed we get

$$A_1 = P_T (\delta_2 - \delta_1) + \frac{E^2}{X_b} (\text{Cos } \delta_2 - \text{Cos } \delta_1)$$

$$A_2 = \frac{2E^2}{X_b} \text{ Cos } \delta_2 - P_T (\pi - 2\delta_2)$$

The requirement for stability is that $A_2 > A_1$. Thus by setting up this equation and simplifying terms

$$\frac{E^2}{X_b} (\text{Cos } \delta_2 + \text{Cos } \delta_1) > P_T (\pi - \delta_2 - \delta_1) \qquad \text{IV-3}$$

Appendices I, II, and III indicate how to calculate X_a and X_b (called Z_{XY}) from the configuration of the system and the type of abnormality under consideration. The angles δ_1 and δ_2 would then be calculated from the following equations

$$P_T = \frac{E^2}{X_a} \text{ Sin } \delta_1 \qquad \text{IV-4}$$

$$P_T = \frac{E^2}{X_b} \text{ Sin } \delta_2 \qquad \text{IV-5}$$

It should be recognized that the simple approach described above neglects such important factors as high speed steam control to the turbines, generator voltage regulator action and time. This approach also assumes that the impedance changes from some initial value to some new value and remains at the new value. This is not the case in the event of a fault. For example, if a single-phase-to-ground fault were to occur on one of the lines of Figure 1, the impedance would

change to, and remain at, some new value for about three cycles until the faulted phase was cleared, at which time, the impedance would change to the value that exists with one pole open. It would remain at that value for about 20 – 30 cycles, at which time, the impedance would return to its initial value when the breaker is automatically reclosed.

Thus, there are three (rather than two) power curves that should be considered for the case of faults. However, it is assumed that the duration of the fault is short compared to the duration of the open phase, and if it is further considered that the power transfer impedance (Z_{XY}) for the condition of a single phase-to-ground fault is not too different from that for the condition of one pole open, then it is a reasonable approximation to assume the system goes from a normal state directly to a condition of one pole open in this simplified approach.

In any event, the approach is quite conservative because it assumes that the system remains with the one pole open until stability is either lost or established. In an actual situation, the open pole may very well be reclosed long before the angle swings to ($\pi - \delta_2$) As indicated in Figure IV-B this yields an area A_2 which is significantly greater than A_1. Exactly where in time and angle (δ_3) the change would take place can be evaluated by a complete transient stability study. However, if the simple approach outlined in this Appendix indicates a stable situation it will be stable in real life. On the other hand a system found to be unstable by this method may in fact be stable.

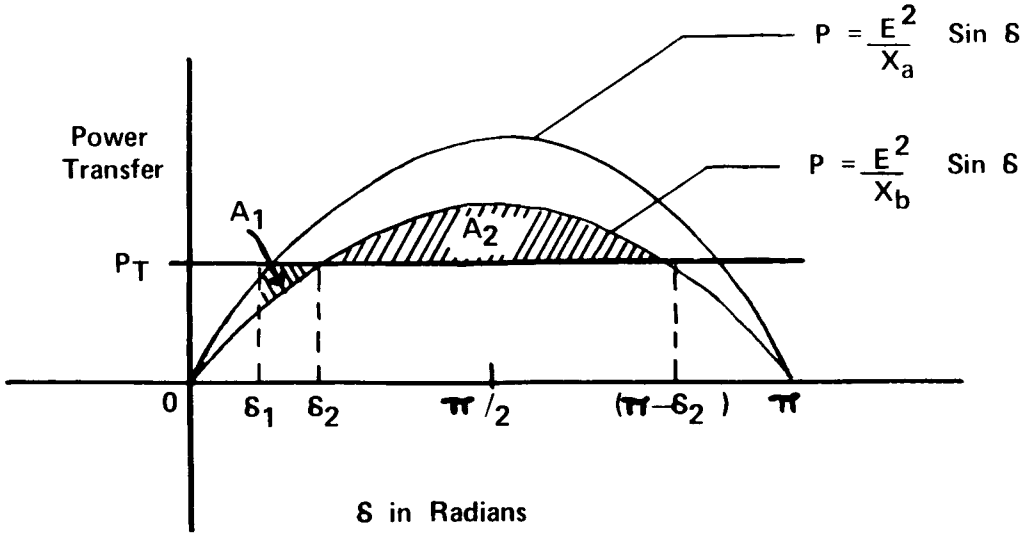


Figure IV-A

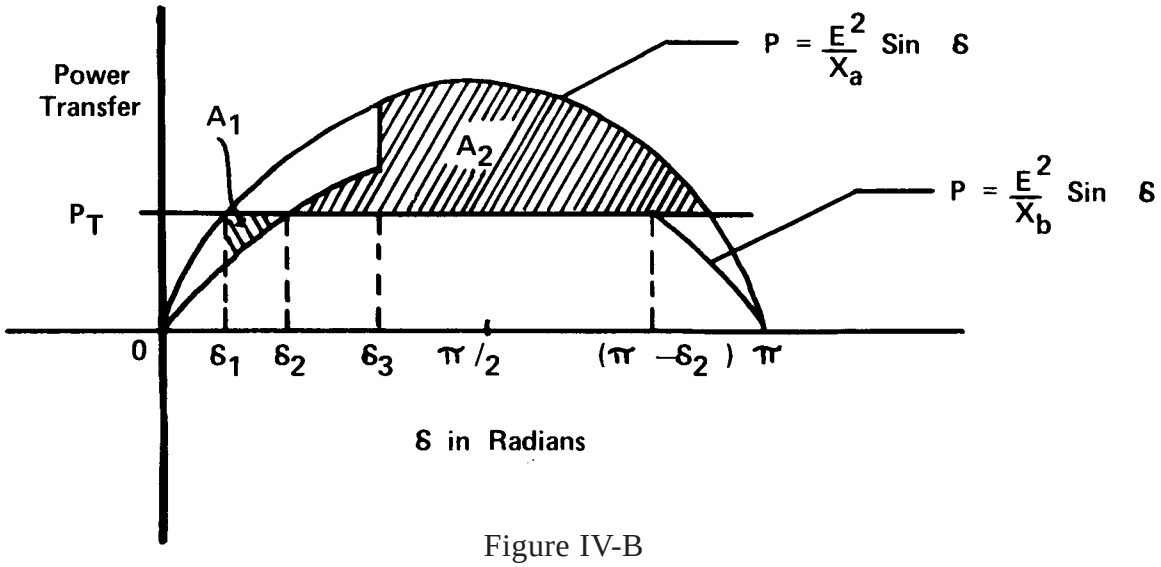


Figure IV-B

where:

E = The transmission system voltage in volts

P_T = The power transfer across the system in watts prior to the disturbance

X_a = The power transfer reactance of the system before the disturbance

X_b = The power transfer reactance of the system after the disturbance

δ_1 = Angle in radians across the system prior to the disturbance

δ_2 = Angle in radians across the system after the disturbance.